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Abstract: We present results from a novel single-transient x-ray detection system with a temporal resolution of ~1ps. The approach relies upon the x-ray induced modulation of the optical index of refraction to amplitude modulate a probe beam. The amplitude modulated probe beam is then recorded on an ultrafast single-shot time lens recording system.

I. INTRODUCTION

Prompt diagnostics of fusion burn at the National Ignition Facility will require temporal resolution of 1ps or better. Most conventional x-ray (and other ionizing radiation) detectors yield a signal by producing electrons (and holes in the case of semiconductor based detectors), and transporting, or otherwise manipulating the produced charge to form a signal. Usually, the transport and manipulation of charged particles is what limits the achievable temporal response of these detectors. In our approach we use x-rays to directly modulate the amplitude of an optical probe beam without the transport of charged particles.

We have long been interested in directly modulating a probe beam with ionizing radiation as it passed through a semiconductor[1]; but these early approaches were lacking a well-understood physics framework. Later, work in all-optical switching came to our attention (such as Park[2]), furnishing a much better-understood physical framework. All-optical switching is usually defined as "light switching light". Many approaches to all-optical switching rely upon an optical pump beam which produces a relatively high-density of electron-hole (e-h) pairs. Through various mechanisms this modulation of the e-h pair density produces a change in the optical index of refraction that is seen by a probe beam (thereby producing a mechanism to control or switch the probe beam). As noted above, most x-ray detectors function by the production of charge when x-rays interact with matter; it is then natural to suppose that x-rays could be used to modulate the index of refraction directly. We then successfully demonstrated the existence of a radoptic effect[3]; showing a significant negative index shift was associated with the absorption of x-rays, and we began work to develop fieldable detectors[4].

II. THE RADOPTIC EFFECT

Figure 1 illustrates a snapshot of phase objects (local regions of modified optical index) created by intercepting a beam of x-rays, particle fluence, $\psi(\text{xrays}/\mu\text{m}^2)$ and particle energy, E_{rad} while simultaneously propagating an optical probe with beam area A_{mode} through the same volume of semiconductor. The total phase shift, $\phi = N_x \delta\phi$, where N_x is the number of x-rays absorbed in the volume illuminated by the probe beam, and $\delta\phi$ is the phase shift in the probe due to a single phase object and is given by, $\delta\phi = E_{rad} / A_{\text{mode}}\ \kappa$, (see ref. 4).

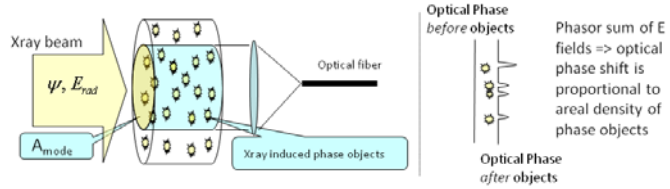

Fig 1. Probe modulation by x-ray produced phase objects

The spatial extent of the e-h cloud and presumably the phase object is very small, ~10^{-4} μm^3 (e.g., for 10 keV x-rays in Carbon, see ref. 5). Finally, κ (milliradians-keV/μm^2) is a parameter that represents the intrinsic sensitivity. The total phase shift is then given by, $\phi = \kappa\tilde{\psi}$ where $\tilde{\psi}$ = the absorbed x-ray energy fluence (keV/μm^2).

The quantity ϕ is proportional to the signal amplitude that we measure; it is significant to note that this quantity is *independent of detector area*. This means the detector can be made quite small without sacrificing signal quality (subject to the limitations of particle statistics within the detector area, of course). Thus, in some sense x-ray imaging comes for free; differing significantly from conventional detection technology. The GATOR approach (ref. 6) exploits these imaging characteristics very efficiently.

We now generalize to a time-dependent x-ray intensity $S(t)$, which we measure in units of keV/μm^2-ps of absorbed x-ray energy, and recognize that the fundamental phase shift from each phase object has a temporal history characterized by a generation time, and a relaxation time, τ_g and τ_r, respectively. So, in general the total phase shift is given by $\phi(t) = \int_{-\infty}^{\infty} S(t-\tau)\kappa(\tau, \tau_g, \tau_r)d\tau$, where, our x-ray sensitivity parameter becomes time-dependent $\kappa \to \kappa(\tau, \tau_g, \tau_r)$. In the case where τ_g is very small and τ_r is long compared to the timescales of the x-ray signal, the sensitivity

parameter becomes a step function, $\kappa(\tau) = \kappa\theta(\tau)$ and the phase shift can be written as,

$$\phi(t)_{\text{integrating}} = \kappa\int_{-\infty}^{t} S(\tau)d\tau; \qquad (1)$$

In another limit, if both τ_g and τ_r are small the sensitivity parameter is proportional to the Dirac delta function and

$$\phi(t)_{impulsive} = \int_{-\infty}^{\infty} S(t-\tau)\hat{\kappa}\delta(\tau)d\tau = \hat{\kappa}S(t). \quad (2)$$

The relationship between κ and $\hat{\kappa}$ is complex and depends upon the details of the time-dependent $\kappa(\tau)$.

III. DETECTION AND RECORDING

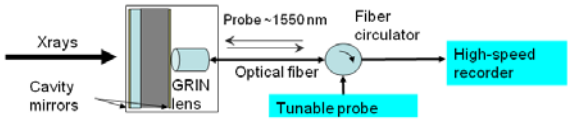

Fig.2. Generalized radsensor system diagram

In our system we use a Fabry-Perot cavity (radsensor) to convert the single-pass phase modulation , $\phi(t)$, to an amplitude modulation which is then recorded on a high-speed single-transient recorder. The recorder used for the results here was the time lens[7] system which has a measured rise-time of 0.9ps. Alternatively the SLIDER[8] system can also be used.

IV. EXPERIMENTAL RESULTS

Our pulsed x-ray source was the Callisto laser at LLNL's Jupiter Laser Facility, operating at 800 nm with 60fs optical pulses, shooting 12.5 micron Cu targets, yielding ~8keV Cu-k_α radiation, lower energy bremsstrahlung, and high energy electrons absorbed within the radsensors.

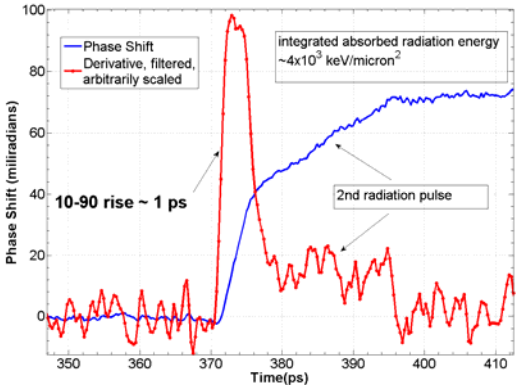

Fig. 3. "Integrating" detector x-ray response, shot 79.

Our radsensor detectors had an active region of epitaxially grown InGaAsP. The "impulsive" detector had an optically measured τ_r ~3ps, due to the introduction of trapping centers by ion bombardment. The "integrating" detector active region was as-grown epi.

The blue trace in figure 3 represents the x-ray induced phase shift for a detector whose response is approximated by Eq. (1). The red-trace is the derivative of the blue trace that has been moderately filtered and arbitrarily scaled in amplitude. The ~1ps rise of the derivative trace demonstrates that τ_g < 1ps. For the integrating detector we estimate that κ ~ 0.05 mradians-keV/μm^2 by our x-ray calibrations.

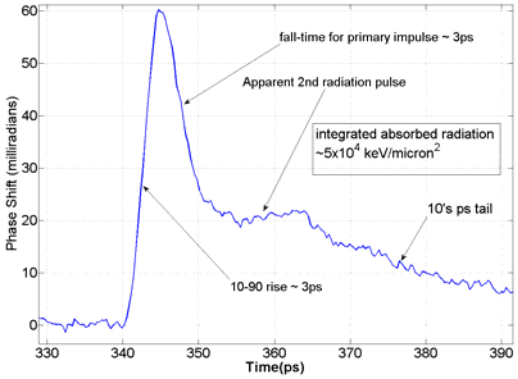

Fig. 4. "Impulsive" detector x-ray response, shot 369.

The response of the "impulsive" detector, figure 4, approximated by Eq. (2), generally follows the shape of the derivate in figure 3, including the apparent 2nd x-ray pulse which was evident in many shots. The signal "tail" could be due to inhomogenous ion implantation or possibly a result of the Callisto laser becoming detuned.

V. DISCUSSION AND CONCLUSIONS

There was significant shot-to-shot variation in the signal rise-times, probably due to fluctuations in the actual x-ray pulses. However, enabled by the speed of the time lens, data presented in figure 3 demonstrates that the intrinsic rise-time of the radoptic effect, τ_g < 1ps, consistent with the ~100 fs e-h pair formation time calculated in ref.5.

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